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A SYSTEM OF STANDARD ATMOSPHERES

by

B N Charles

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ABSTRACT

A family of Standard Atmospheres is devised for defining vertical variations of temperature and pressure. These Atmospheres approximate mean conditions over Eurasia, as deduced from limited climatological data.

A body of data for North America, comprising over 57,000 observations, is compared with these Atmospheres, and it is concluded that the temperature-height curves as herein defined will approximate ambient conditions over the Northern Hemisphere at least 70 percent of the time. The degree of approximation is no greater than that to be inferred from the internal consistency of the defined family of Standard Atmospheres.

Tables are appended showing the temperature, pressure, and density variations with altitude in each of 12 Standard Atmospheres.

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FOREWORD

In connection with certain specialized problems of barometry, it was felt that a more suitable set of Standard Atmospheres was required. This report presents such a set (in Appendix B) and considers its representativeness for the Northern Hemisphere by discussing the method of its construction and the various limitations involved. These limitations arise mainly from the paucity of climatic data and from difficulties in attacking the problem for all possible operational applications.

Temperature-height curves over the world can assume an infinite number of configurations. One extreme might be represented by winter conditions above the Tibetan Plateau and the Greenland Icecap where marked surface inversions of temperature appear at elevations near 10,000 feet above sea level. These conditions have not been included in this report. Also, the anomalous conditions typical of the rough mountainous area of southern Eurasia have not been included because of inadequate data.

The various groupings of data used herein are not always climatologically homogeneous. In general, regional temperatures have been typed according to latitudinal or continental orientations, although the correlation between local and regional phenomena may often be small. This typing, however, should have general validity where modifying factors due to terrain influence are not excessive.

An important consideration in deriving these temperature-height curves was the desirability of keeping the total number of curves to a minimum.

Operational difficulties arising from the aforementioned limitations can be minimized by the utilization of competent meteorological advice in the selection of a Standard Atmosphere to approximate an ambient condition. The meteorologist consulted should be oriented in some detail as to the mechanics of the application.

INTRODUCTION

A known vertical distribution of atmospheric temperature is necessary in various ballistic applications. Conventional Standard Atmospheres such as the NACA*, ICAN†, and Ballistic are inadequate for some of these applications because they deviate excessively from ambient conditions likely to be encountered. The magnitude of these deviations can be reduced by the utilization of several vertical temperature distributions, although the admirable virtue of simplicity characteristic of the unitary Standard Atmosphere is thereby sacrificed.

A family of atmospheric temperature structures is derived herein which is based on meteorological observations and defines mean conditions likely to be encountered over Eurasia.

For convenience, the atmosphere is divided into three vertical regions. The 'low' atmosphere is defined roughly as the lowest 10,000 feet above sea level and is characterized by maximum temporal and spatial variations in temperature. These variations result from inversions and stratifications arising from terrain effects and advection. The low atmosphere will hereinafter be regarded as that portion of the atmosphere lying below the 700-mb‡ pressure level.

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*National Advisory Committee for Aeronautics

†International Commission for Air Navigation

‡The millibar (abbreviated mb) is the meteorological unit of pressure. One millibar is 1000 dynes per square centimeter. Since it is a unit of pressure, the vertical distance in the atmosphere equivalent to a stated increment of millibars is dependent upon the temperature. In the ICAN atmospheres, the relationship between pressure and altitude is:

$$Z = 145,330 \left[1 - \left(\frac{p}{1013.2}\right)^{0.19}\right]$$

where Z is in feet and p is in millibars.

The 'middle' atmosphere is defined as the layer included between the 700-mb and 300-mb pressures. Except for mountainous regions, terrain effects are minimized in this layer, and temperatures are more nearly dependent upon advection and other dynamic processes of the free atmosphere.

The 'high' atmosphere is defined as the layer of air above 300 mb. The tropopause* is usually within this layer, although it can be lower in the colder air masses.

A representation of the hemispheric vertical distribution of temperature and the tropopause is shown in Fig. 1.

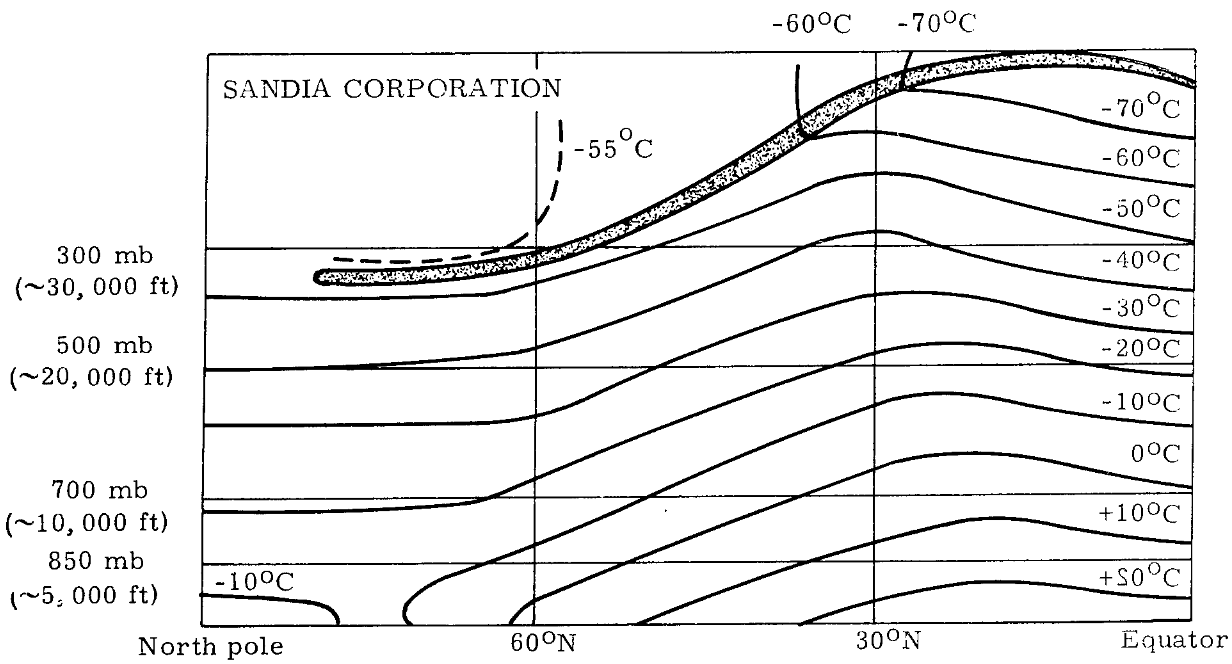

Fig. 1 -- Schematic temperature cross section of Northern Hemisphere (shaded area is the tropopause)

The temporal variations of vertical temperature structure at a given location on the earth are large. One classification scheme for air masses uses generic identifications such as Arctic, Polar, and Tropical. In this system, an air mass is identified as belonging to one of these categories in accordance with its source region. Additional definition

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*The tropopause is a shallow layer separating the troposphere and the stratosphere. In the troposphere, there is a systematic decrease of temperature with increasing altitude, while in the stratosphere the temperature is near-isothermal or may even increase with altitude. The height of the tropopause is normally greater in low latitudes than in high latitudes (see Fig. 1).

is provided by use of the terms Maritime and Continental. Thus, an air mass moving southeastward through the United States might be Polar Continental, while one which invades from the Gulf of Mexico would be Tropical Maritime. It is found that the vertical thermal structures of air masses within a given classification exhibit reasonable similarities. The purpose of this discussion is to design a family of vertical temperature structures which will approximate ambient structures over Eurasia.

THE MIDDLE ATMOSPHERE

It is most convenient to consider first the layer of air between 700 and 300 mb. Riehl and LaSeur[1] have shown that the lapse-rate* in this region may be regarded as consisting of two parts: an average lapse-rate which is a linear function of the mean temperature of the layer, and a deviation from this mean lapse-rate that depends upon the synoptic situation. This conclusion was evolved from a study of more than 3000 temperature-height curves over North America, but can be considered as representative of the entire Northern Hemisphere, as some correction was made for effects of mountainous terrain. The average lapse-rate in the layer from 700 to 300 mb was determined to be:

$$\gamma_s = 2.62 \times 10^{-2} \, \overline{T} \tag{1}$$

where γ_s = mean lapse-rate (degrees centrigrade per km) and $\overline{T}$ = mean temperature of the layer (degrees Kelvin).

The 300-mb temperatures corresponding to specified 700-mb temperatures in accord with Equation 1 were found to be as listed in Table I.

TABLE I

300-mb Temperatures Corresponding to Specified 700-mb Temperatures and the Mean Lapse-Rate of Riehl and LaSeur

700-mb temp ($^{\circ}$C)	300-mb temp ($^{\circ}$C)	Mean temp ($^{\circ}$K)	Lapse-rate ($^{\circ}$C/1000 ft)
+20	-27	269.5	2.15
+10	-34	261.0	2.08
0	-42	252.0	2.02
-10	-50	243.0	1.94
-20	-57	234.5	1.88
-25	-60	230.5	1.84

*The term 'lapse-rate' means the rate of decrease of temperature with increasing altitude.

Some interesting properties of the 700-300 mb layer reported by or deducible from the data of Riehl and LaSeur are as follows:

1. The approximate* distribution of mean temperature in the layer was as shown in Table II. (NOTE: To a close order of approximation, the mean temperature is the algebraic mean of the temperatures at the top and bottom of the layer.)

TABLE II

Frequency of Mean Temperature of the 700-300 mb Layer

Mean temp (°C)	-10	-15	-20	-25	-30	-35
Frequency (%)	15	21	22	22	15	5

2. Excluding the upper and lower deciles, the maximum deviation of actual lapse-rates from the mean defined in Equation 1 was 1.5°C/km, or about 0.4°C/1000 feet. These statistics imply that for a given temperature at 20,000-feet altitude, the assumption of the lapse-rate of Equation 1 will result in a maximum temperature error at 10,000-feet altitude of less than 4.0°C in 80 percent of all cases.

3. Deviations from the mean lapse-rate showed the following consistent features:

a. The most unstable† lapse-rates were associated with stations in the lee of mountains.

b. The more stable lapse-rates were associated with the protrusion of cold air above the 700-mb level. Generally, temperatures less than -20°C at the 700-mb level indicate this condition.

Both conditions cited in Paragraph 3 above modify the coefficient of Equation 1. Since the importance of these modifications is reasonably small, as outlined in Paragraph 2 above, it is not deemed necessary to treat them separately.

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*Figures interpolated from Fig. 3a of Reference 1.

†Larger, ie, more negative.

Standard Atmospheres for the layer included between the 700- and 300-mb pressure levels can be defined from Equation 1 by specifying a temperature at 700 mb and interpolating the temperature at 300 mb from Table I. In specifying the range of temperature at 700 mb, it is helpful to refer to normal weather charts[2] wherein it is found that the isopleths of the maximum and minimum normal monthly temperatures at 700 mb over the Northern Hemisphere are $+15^{\circ}C$ and $-30^{\circ}C$. Extreme temperatures[3] show a range at 10,000 feet (nearly the 700-mb pressure level) of $+25^{\circ}C$ to $-50^{\circ}C$. It is not prudent to attempt the construction of Standard Atmospheres encompassing extreme conditions which are but infrequently encountered. From the writer's experience in analyzing weather charts for Europe and Asia, it is estimated that temperatures of $+20^{\circ}C$ and $-35^{\circ}C$ were observed with sufficient frequency at the 700-mb pressure level to merit their approximation by an array of Standard Atmospheres. Temperature frequency data[4] show that temperatures at the 3-km level outside of the range $+20^{\circ}C$ to $-35^{\circ}C$ are encountered as shown in Table III.

TABLE III

Frequencies of Certain Temperatures at 3 km

Location	Greater than $+20^{\circ}C$	Less than $-35^{\circ}C$
San Diego, Cal.	Less than 2%, summer	
El Paso, Texas	Less than 8%, summer	
Anchorage, Alaska		Less than 1%, winter
Barrow, Alaska		Less than 5%, winter

From these considerations and the desirability of limiting the quantity of Standard Atmosphere structures, the range of temperature at the 700-mb pressure level is arbitrarily set at $-33^{\circ}C$ to $+17^{\circ}C$.

The total range of 50 C° suggests an interval of 10 C° between standard structures at the 700-mb pressure level, thereby limiting the number of structures in the middle atmosphere to six. This separation is arbitrary.

The geometric thickness of a layer in the atmosphere is given by the hypsometric formula:

$$\Delta z = \frac{R\overline{T}}{g} \ln \frac{P_1}{P_2} \qquad (2)$$

where

Δz = thickness (in cm),

R = gas constant for air (in metric units),

g = acceleration of gravity (in metric units),

P_1 and P_2 = the lower- and upper-level pressures, respectively, and

$\overline{T}$ = mean temperature of the layer P_1 to P_2 (in ^{o}K).

After substitution of appropriate quantities and necessary conversion factors to yield Δz in feet, Equation 2 reduces to (see Appendix A, Paragraph 2):

$$\Delta z = 81.41 \, \overline{T} \text{ feet} \tag{3}$$

Values of the 300-mb temperature and the thickness of the 700- to 300-mb pressure layer corresponding to assigned values of temperature at 700 mb in accord with the preceding discussion are then as shown in Table IV, together with arbitrary atmosphere designations.

TABLE IV

300-mb Temperatures and 700- to 300-mb Thicknesses
Corresponding to Specified 700-mb Temperatures

Atmosphere designation	700-mb temp (^{o}C)	300-mb temp (^{o}C)	700 to 300-mb layer $\overline{T}$ (^{o}K)	(ft)
66	-33	-66	223.7	18,200
65	-23	-59	232.2	18,900
64	-13	-52	240.7	19,600
63	-3	-44	249.7	20,300
62	+7	-36	258.7	21,100
61	+17	-29	267.2	21,800

In the preceding discussion, the level of the tropopause has been ignored. It is frequently observed that in cold atmospheres this level is below that of the 300-mb pressure. It is conventional to assume isothermal conditions immediately above the tropopause. For those instances in which the tropopause lies in the middle atmosphere, the Standard Atmosphere will be considered to have the previously defined standard lapse-rate up to the level of the tropopause, and thereafter will be considered isothermal through the altitude range pertinent to its application. The quantities in Table IV are therefore tentative, pending determination of the tropopause level in each Atmosphere.

The <u>mean</u> height of the tropopause varies between 27,000 and 55,000 feet above sea level.[5] In a general way, the lesser height may be associated with high latitudes or colder atmospheres, and the greater height with low latitudes or warmer atmospheres. The warmest and coldest atmospheres of the six previously proposed were chosen to approximate relatively extreme temperature conditions aloft, and therefore are not representative of mean warm or mean cold types. It is reasonable, however, to consider their adjacent structures as such. As an approximation, then, the tropopause is fixed at 27,000 feet in Atmosphere 64 and at 55,000 feet in Atmosphere 62. To determine the temperatures at these tropopauses, the temperature structures between sea level and the 700-mb pressure level must be known.

THE LOW ATMOSPHERE

The temperature structure in the lower troposphere is exceedingly variable, due to the anomalies mentioned earlier. A single standard lapse-rate such as was previously defined is not realistic due to the frequent juxtaposition of warm and cold air masses, with attendent large variations in the low-level lapse-rates. About all that can be said is that in a very warm atmosphere the lapse-rate will be near adiabatic ($10^{\circ}C/km$) in the low levels, while in the very cold atmosphere there is usually an inversion of temperature so that the temperature at the ground is often colder than that at elevations of two or three kilometers. The magnitude of this inversion is sufficiently variable as to dictate the use of alternate temperature structures below the 700-mb pressure level.

Flohn[6] presents some conclusions concerning the low-level inversion in arctic climes as follows:

1. The lower the ground temperature, the greater the elevation of the upper level of the inversion layer. (For surface temperatures less than $-40^{\circ}C$ at Yakutsk for example, over 75 percent of the inversion upper limits were in the 600- to 700-mb layer. With ground temperatures greater than $-25^{\circ}C$, the incidence of upper-inversion levels in that layer was 33 percent, with all other upper-inversion levels at lower elevations.)

2. The magnitude of the inversion is $10\text{-}24^{\circ}C$ in 65 percent of the Yakutsk cases (243 in all). About six percent of all cases had greater magnitudes.

The foregoing suggests two alternatives for Atmosphere 66: (1) a structure from the 650-mb pressure level to a surface temperature of -40°C, and (2) a structure from 650 mb to a surface temperature of -25°C.

Comparison of winter temperature structures for Central Europe and Yakutsk (data from Flohn) shows that if the 700-mb temperatures are about -25°C in both, the temperature structures above that level are quite similar, but Yakutsk has a mean surface temperature of about -23°C (top of inversion layer about 5000 feet) while Central Europe has a mean surface temperature of about -11°C (no inversion layer). Atmosphere 65 approximates the 700-mb temperature of -25°C; therefore, alternate structures below 700 mb are necessary.

Atmosphere 64 has a 700-mb temperature of -13°C. Data from the USWB[7] and Petterssen[8] are presented in Table V, showing mean situations typical of this 700-mb temperature and concurrent temperatures at other levels.

TABLE V

Weather Situations Producing Mean 700-mb Temperatures Near -13°C, and Concurrent Temperatures at Other Levels

Situation	Temperature (°C) 1000 mb	Temperature (°C) 500 mb
Summer Arctic air: Murmansk and Archangel	+9	-27
Polar Maritime air: Lindenburg, Berlin, and Breslau	+2	-28
Arctic air having passed the Norwegian Sea: Lindenburg, Berlin, and Breslau	+2	-32
Arctic air having passed the Norwegian Sea: Hamburg, Kiel, and Norderney	+3	-30
Winter at Astrakhan	-5	-29
Winter at Rostov or Kiev	-6	-29
Winter at Odessa	-3	-26

Atmosphere 64 reasonably approximates the temperatures at 700 and 500 mb in the foregoing cases, but it appears that provision must be made for a range of temperature at 1000 mb from about +10°C to -8°C. European air mass data[9] indicate that with a 700-mb temperature of about -13°C, the preferred 1000-mb temperature is about +7°C. The alternate structures for Atmosphere 64 are therefore fixed to yield 1000-mb temperatures of +6°C and -8°C. The colder alternate (Atmosphere 64A) is assumed near-isothermal to the 790-mb level.

Atmosphere 63 corresponds to a 700-mb temperature of -3°C. Table VI lists some situations typical of this, together with temperatures at other levels, from data of References 7-10.

TABLE VI

Weather Situations Producing Mean 700-mb Temperatures Near -3°C, and Concurrent Temperatures at Other Levels

Situation	Temperature (°C) 1000 mb	500 mb
Tropical Maritime air in winter: Nancy, Cologne, and Frankfurt	+9	-19
Polar Maritime air in summer: Helsinki, Utti, and Slutsk	+14	-19
Warmest months over:		
Irkutsk	+16	-19
Archangel	+14	-17
Cold Polar air in summer: Europe	+18	-22
Polar Continental air in winter: Nanking	+9	--

As an approximation, therefore, the alternate structures for Atmosphere 63 should yield 1000-mb temperatures of +10°C and +17°C. Subjective fitting of available data results in extending the colder alternate to about 610 mb.

The 700-mb temperature of +7°C in Atmosphere 62 is approximated by situations with temperatures at other levels as shown in Table VII.

TABLE VII

Weather Situations Producing Mean 700-mb Temperatures Near +7°C, and Concurrent Temperatures at other Levels

Situation	Temperature (°C) 1000 mb	500 mb
Tropical Continental air in summer: Moscow, Smolensk, Kiev, and Cracow	28*	-10
Yakutsk: summer[6]	15	-14
Tropical air: Europe[9]	25	-12
Monsoon air, winter: Poona, India[8]	27	-9
Polar Continental air, summer: Nanking[10]	27*	--

*Extrapolated from 900-mb data.

Subjective fitting of available data yields two structures with 1000-mb temperatures of +27°C and +19°C, with the colder one distinct up to the 510-mb level.

Atmosphere 61 has a 700-mb temperature of +17°C. This corresponds roughly to the warmest structures observed at Salton Sea Test Base, and to the warmest found in data for Bahrein (Persia), Jodhpur (India), and Colomb (French Morocco). Situations and temperatures at other levels corresponding to the 700-mb temperature of +17°C are listed in Table VIII.[11]

TABLE VIII

Weather Situations Producing Mean 700-mb Temperatures Near +17°C, and Concurrent Temperatures at other Levels

Situation	Temperature (°C) 1000 mb	500 mb	300 mb
SSTB: summer	+35 to +47	-5 to +2	-24 to -32
Colomb: June 27, 1950	+46	-9	-32
Jodhpur: July 26, 1950	+34	0	-22
Habbaniya: July 25, 1950	+29	+2	-25
Bahrein: August 6, 1950	+43	+1	-26

The data for Colomb showed an approximately adiabatic lapse-rate below 530 mb. Indeed, there was a superadiabatic layer from 530 mb to 700 mb. In effect this described Atmosphere 62 above 700 mb, and Atmosphere 61 below that level. The Habbaniya data, on the other hand, indicated the mixture of Atmosphere 62 and Atmosphere 61, with the former in the lower levels. The Colomb data describe the unstable conditions due to the excessive low-layer heating experienced in tropical desert interiors, and are not representative of probable areas of application. The mixed situation at Habbaniya, however, is a reasonably probable situation in warm regions, and suggests a lower alternate for Atmosphere 61, which approximates Atmosphere 62 conditions. Subjective fitting of available data results in 1000-mb temperatures of +30°C and +40°C, with the colder alternate extending separately to 650 mb. Figure 2 shows the temperature structures thus far defined.

To complete the structures, the pressure and temperature at a given geometric level in each Atmosphere must be known, so that the temperature-height variation may be computed by Equation 2. For this purpose, it is most convenient to consider sea-level pressure. Extremely low temperatures are always accompanied by high sea-level

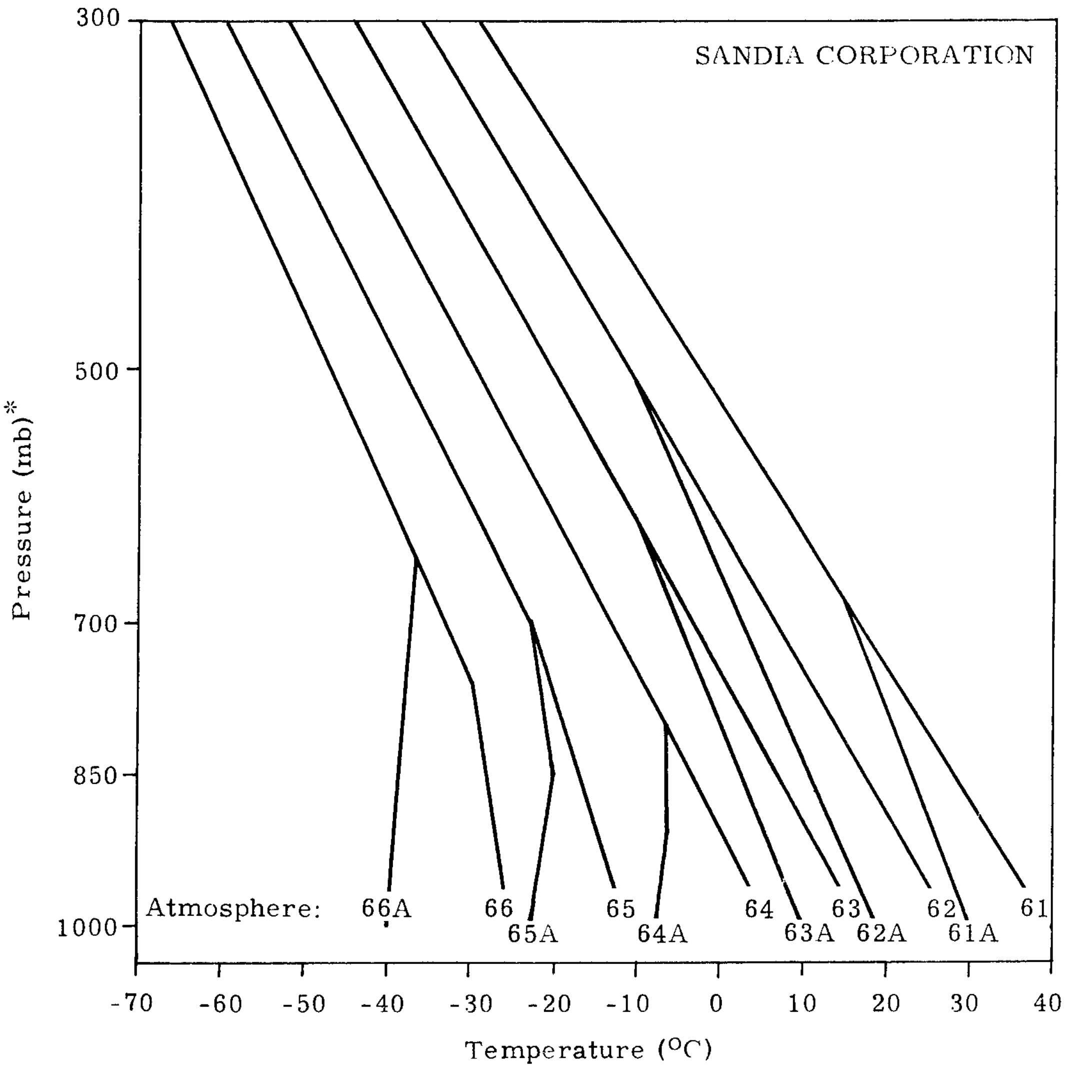

Fig. 2 -- Tentative Standard Atmospheres; structure above 300 mb to be defined

*Ordinate scaled as 0.288 power of pressure in accord with Poisson's Law for adiabatic processes. Atmospheric processes are near adiabatic, and with this scale, distances on the chart are approximately proportional to distances in the atmosphere.

pressures. The greatest expectancies of January temperatures below -40°C occur in northeast Siberia, northwest Canada, east-central Alaska, and over the Greenland Ice-cap.[12] In general, the coldest area of the Northern Hemisphere is in Siberia, near Verkhoyansk and Oimekon. January mean sea-level pressure[2] in that region is about 1025 mb, but observations of 1050 mb are not uncommon. In northwestern Canada, January mean sea-level pressures[2] are about 1020 mb and observations of 1040 mb are not uncommon. It seems safe to assume that sea-level pressure during extremely low surface temperatures is within 35 mb of 1035 mb. From Fig. 2 it is seen that in the coldest structures (Atmospheres 66 and 66A) the maximum temperature departure due to these assumed differences in surface pressure, at a height above the surface, will be about 1 C°. In hot atmospheres, the range of sea-level pressure may be taken as 20 mb about 1000 mb, by arguments similar to those used above. In these cases, the maximum temperature departure due to assuming a sea-level pressure of 1000 mb is about 2 C°. In the intermediate atmospheres, if the range of sea-level pressure is assumed to be 40 mb about 1020 mb, the maximum temperature departure will be about 3 C°. The foregoing departures are less than the maxima to be expected from the differences between actual temperature structures and the defined Standard Atmospheres. Sea-level pressures in the intermediate structures are arbitrarily graded between the aforementioned limits.

THE HIGH ATMOSPHERE

It is now necessary to assign height values to the tropopause in each Atmosphere. It was stated earlier that the range of mean height of the tropopause is 27,000-55,000 feet, and that these values could be associated with Atmospheres 65 and 62. The Arctic tropopause is frequently observed as low as 7.5 km;[13] therefore the tropopause level in Atmosphere 66 is arbitrarily placed at 25,000 feet. The tropical tropopause frequently exceeds an elevation of 60,000 feet, which is above the level of interest in applications of these structures. It is therefore unnecessary to assign a tropopause level to Atmosphere 61. The intermediate structures correspond to mid-latitude air masses, where the variability of tropopause height is a maximum. (Note that in Fig. 1, the change in elevation of the tropopause is greatest in the mid-latitudes.) The range of mean height of the mid-latitude tropopause is 35,000-45,000 feet,[5] and these limiting values are assigned to Atmospheres 64 and 63 respectively.

It should be noted that the upper levels are often of negligible importance in ballistic applications to which these Standard Atmospheres may be pertinent.

POLYNOMIAL APPROXIMATIONS OF THE TEMPERATURE STRUCTURES

Applications of the aforementioned Atmospheres to ballistic problems may involve the use of iterative computational techniques which are best accomplished by machine methods. To facilitate such computations, it is desirable to define the temperature-height profiles in terms of explicit mathematical functions. This requires fitting polynomials to the defined structures. Sandia Corporation Section 5241-2 performed the necessary polynomial fitting, so that negligible changes were made to the original structures. Appendix B lists height, pressure, temperature, and density for the Standard Atmospheres computed by the methods of Appendix A, after polynomial smoothing. Figure 3 shows the Standard Atmospheres as plotted from the data of Appendix B.

REPRESENTATIVENESS OF THE STANDARD STRUCTURES

The utility of any Standard Atmosphere is dependent upon the specific application or the needs of the user. The preceding discussion is based in part upon very limited data for widely separated places, and upon often arbitrary definitions and conditions. Because of these limitations, the defined system of Standard Atmospheres is best described as an estimate of mean hemispheric conditions. Some indication of the accuracy of the estimate might be inferred by comparison of the Standard Atmospheres with independent data.

It will be noted from Fig. 3 that the slopes of the theoretical atmospheres are quite similar above the 700-mb pressure level. All available data indicate that actual temperature structures above that level will be reasonably approximated by one of the Standard Atmospheres. In the lower levels, however, more variability in temperature-height relationship is to be expected, and alternate temperature-height configurations have been provided. The representativeness of these alternates can be tested by the use of bivariate frequency distributions of temperature. These should show the conditional distribution of temperature at some lower elevation when the temperature at the 700-mb pressure level is specified.

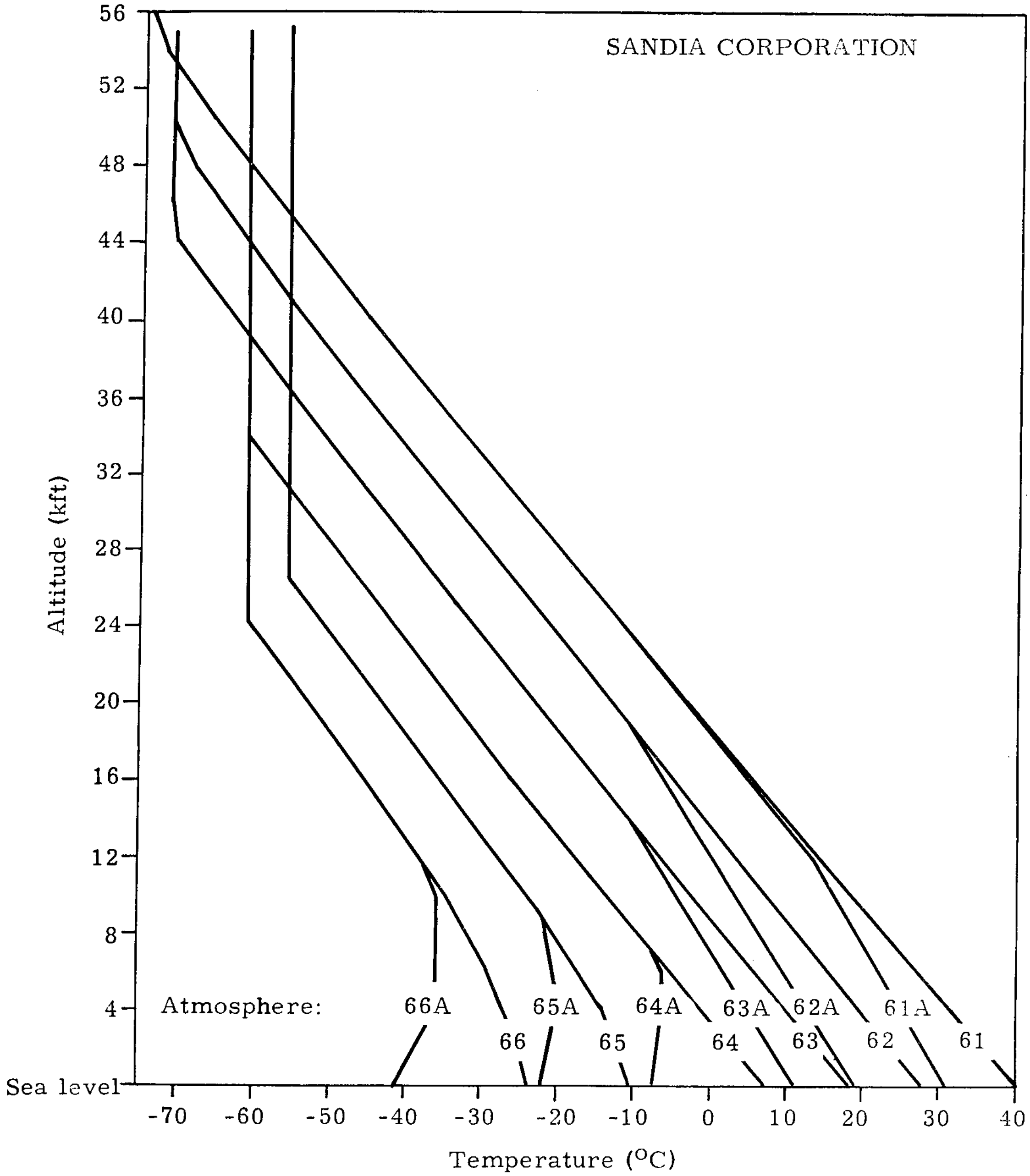

Fig. 3 -- Standard Atmospheres

If, for example, it can be shown that the low-level alternates of a given Atmosphere include most of the temperature distribution at the 850-mb level, while the 700-mb temperature is near that of the same Atmosphere, then that Atmosphere is adequately[*] descriptive of temperature-height curves likely to be encountered.

The most nearly applicable temperature distribution data which could be obtained[†] was a compilation of the frequencies of 850-mb temperatures occurring with specified 700-mb temperatures.[14]

Limitations of data available on punch cards restricted the study to North American stations[‡], and the utilization of 850-mb data rather than that at a lower level. The 850-mb pressure level occurs in the Standard Atmospheres at altitudes of 4400-4800 feet above sea level.

Sixteen stations were selected for study, on the basis of general climatic regimes and continental exposures. Geographic classification by climate is a very complex problem, because of the many variables involved. The stations were broadly selected to provide data for locations ranging from tropical to arctic, and having western, interior, and eastern continental exposures. Such broad coverage, it was hoped, would provide information typical of hemisphere-wide natural conditions. Table IX lists the stations, their locations, and their surface climatic temperature classifications.

It may be seen from Table IX that the stations selected favor hot-to-mild summers and cool-to-cold winters.

Temperatures recorded at each location twice daily (0300Z and 1500Z) from 1948 through 1952 were included in the summary, for a total of 57,667 observations.

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[*] The practical limitation here is the internal consistency of the defined Standard Atmospheres. Thus, at the 700-mb level, the permissible difference between ambient and standard conditions is 5 C°, but at lower levels it is some smaller figure determined by the ranges of temperature included between adjacent Standard Atmospheres.

[†] Sincere appreciation is expressed to Major R. Arnold of the 1st Air Weather Group, and the Directorate of Climatology, Air Weather Service, USAF, for furnishing this material so expeditiously.

[‡] It may be generally assumed that above the level of strong terrain influence (the 'gradient level'; ie, about 2000 feet above the ground) temperature-height curves are independent of geographical location.

TABLE IX

Stations Included in Reference 14, and Their Climatic Temperature Classifications

	Station	Location		Classification[15]	
		Lat (^{o}N)	Long (^{o}W)	Summer	Winter
Western	Annette Island	55	132	Mild	Cool
	Bethel	61	162	Cool	Cold
	Barrow	71	156	Cool	Cold
	Medford	42	123	Mild	Cool
	Oakland	38	122	Mild	Cool
	San Diego	33	117	Hot	Mild
Interior	Columbia	39	92	Hot	Cool
	Joliet	42	88	Hot	Cold
	Omaha	41	96	Hot	Cold
	Oklahoma City	35	98	Hot	Cool
	Sault Ste. Marie	46	84	Mild	Cold
	St. Cloud	46	94	Hot	Cold
Eastern	Buffalo	43	79	Hot	Cold
	Washington	39	77	Hot	Cool
	Charleston	33	80	Hot	Cool
	Miami	26	80	Hot	Mild

Value of Classification Terms

Hot: Mean surface temp $> 20^{o}C$
Mild: Mean surface temp 20 to $10^{o}C$
Cool: Mean surface temp 10 to $0^{o}C$
Cold: Mean surface temp $< 0^{o}C$

Unfortunately, the ten-degree increments of temperature used do not permit detailed verification of the Standard Atmospheres. Several interesting indications can be deduced, however.

Table X shows the frequency of occurrence of 850-mb temperatures while 700-mb temperatures were in specified intervals.

The data in the Totals columns of Table X show the univariate distributions of temperature at the two levels, independently of each other. These are plotted in Fig. 4 as histograms. The sloping lines of Fig. 4 separate the ranges of temperature which are provided for by each Standard Atmosphere previously defined. If it is assumed that the data of Table X are broadly representative of hemisphere conditions*, then the relative usefulness of each Atmosphere may be estimated. Although the distributions within each temperature increment are unknown, it is possible to estimate the relative frequencies of occurrence of each Atmosphere at each level. For example, Fig. 4 shows that at the 700-mb level, Atmospheres 62 and 62A occur about 43 percent of the time, while at the 850-mb level, their frequency is about 36 percent. Similarly, Atmospheres 63 and 63A are applicable at each of the two levels about 29 percent of the time.

The bivariate distribution of the temperature is plotted in Fig. 5. It is apparent from the distribution that the mean 850-mb temperatures are reasonably close to model values. This conclusion from Fig. 5 is dependent upon the fact that the temperature data are serial, and daily temperatures, like many other meteorological parameters, have significant auto-correlation. The foregoing conclusion could not be inferred for randomly varying data because of the size of increment used.

The fact that temperature distribution at any location is reasonably smooth permits the estimation of the probability that any temperature-height curve encountered (between 700 and 850 mb) will be approximated by one of the Standard Atmospheres previously defined. The probability that 700-mb temperature will be in the range applicable to each Standard Atmosphere can be estimated from Fig. 4. Similarly, the probability that the 850-mb temperature will be in a range applicable to any Standard Atmosphere while the 700-mb temperature is in the range applicable to the same Atmosphere can be estimated from Fig. 5. The joint probability, ie, the probability that a given Atmosphere applies

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*One exception may be noted. The northern stations used in Reference 14 are not typical of winter source regions such as the interior of Siberia. If data for this area had been included, the distributions of Table X and Fig. 4 would show slightly higher frequencies in the range of temperature colder than -20°C.

TABLE X

Frequency (and Percent) of Occurrences of 850-mb Temperatures With Specified 700-mb Temperatures (in ^{o}C), 1948-52, 0300Z and 1500Z Data Combined, for the 16 Stations Listed in Table IX

850 mb \ 700 mb	-39 to -30	-29 to -20	-19 to -10	-9 to 0	0 to 9	10 to 19	Totals
-39 to -30	33(*)	3(*)					36(*)
-29 to -20	157(0.3)	777(1.4)	41(*)	4(*)			979(1.7)
-19 to -10	5(*)	1499(2.6)	2455(4.3)	145(0.3)	1(*)		4104(7.1)
-9 to 0		177(0.3)	6736(11.7)	4942(8.6)	55(*)	1(*)	11911(20.8)
0 to 9		9(*)	380(0.7)	11187(19.3)	5318(9.2)	6(*)	16900(29.3)
10 to 19			2(*)	705(1.2)	18486(32.0)	1309(2.3)	20502(35.6)
20 to 29				3(*)	910(1.6)	2321(4.0)	3234(5.6)
Totals	195(0.3)	2465(4.3)	9614(16.7)	16986(29.4)	24770(42.8)	3637(6.3)	57667

*Less than 0.1 percent

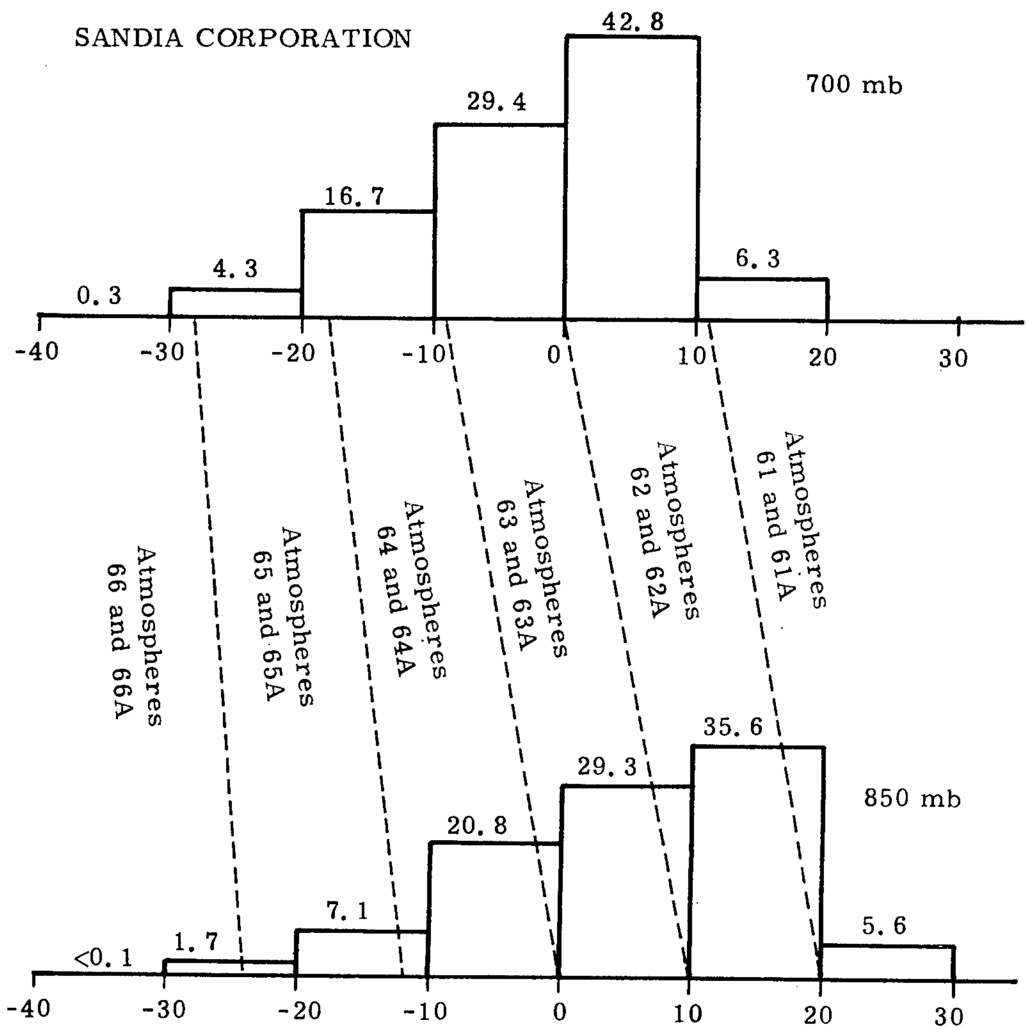
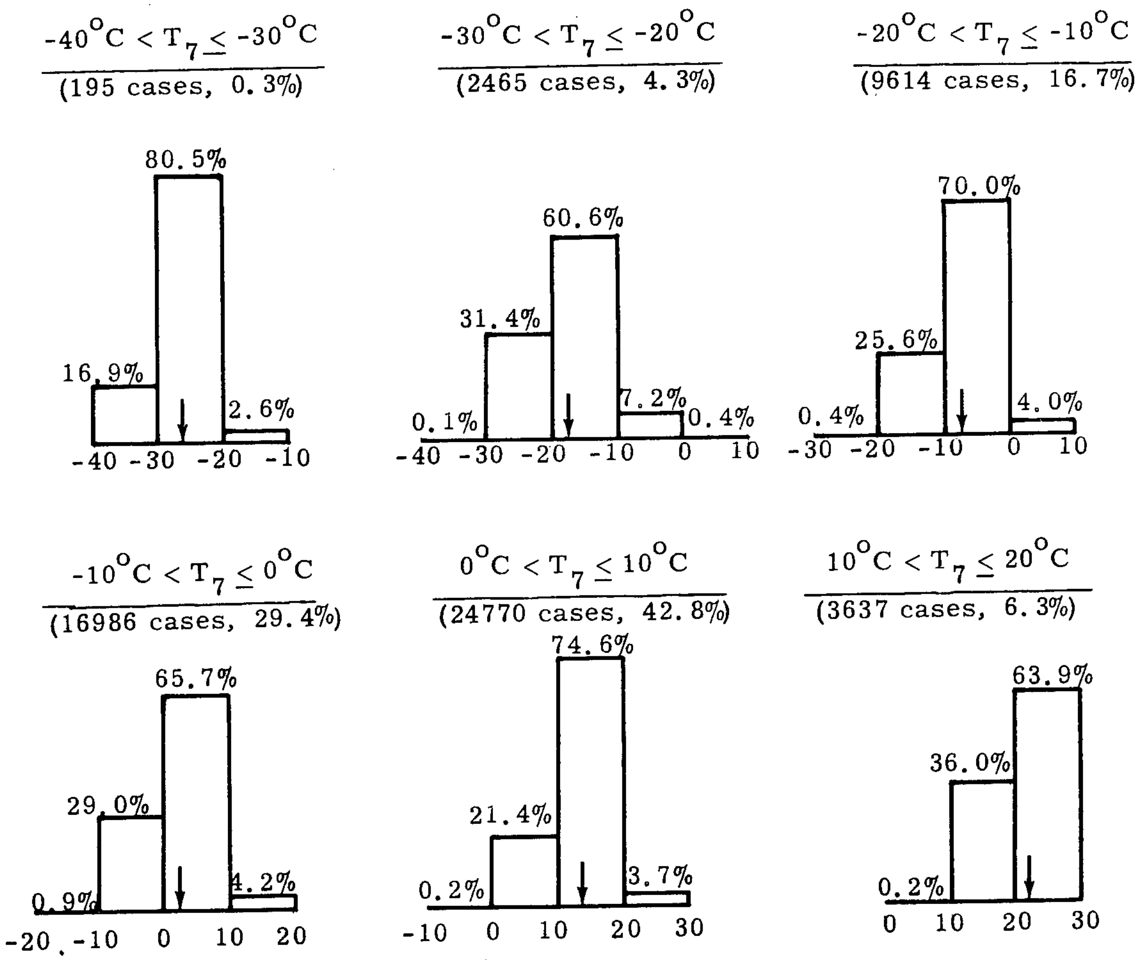


Fig. 4 -- Percent frequency of various temperatures at 700 mb and 850 mb (sloping lines indicate regions of each Standard Atmosphere of this report; all temperatures in ^{o}C)



T_7 = 700-mb temperature

Fig. 5 -- Percent frequency of 850-mb temperatures occurring with specified 700-mb temperatures (arrows indicate group means)

simultaneously at both levels, is then the product of the previously obtained probabilities. Symbolically:

$$P(A_8, A_7) = P(A_7) \times P\left[A_8 \middle| A_7\right] \tag{4}$$

where

$P(A_8, A_7)$ is the probability that temperatures at 850 mb and 700 mb are typical of Atmosphere A simultaneously,

$P(A_7)$ is the probability that temperature at 700 mb is typical of Atmosphere A, and

$P\left[A_8 \middle| A_7\right]$ is the probability that 850-mb temperature is typical of Atmosphere A if the 700-mb temperature is typical of Atmosphere A.

Table XI lists the values of each term, as estimated from Figs. 4 and 5.

TABLE XI

Probabilities that the Standard Atmospheres will Approximate Natural Conditions at 700- and 850-mb Levels

Atmosphere	$P(A_7)$	$P\left[A_8 \middle| A_7\right]$	$P(A_8, A_7)$
66 and 66A	0.01	0.65	0.01
65 and 65A	0.06	0.61	0.04
64 and 64A	0.16	0.75	0.12
63 and 63A	0.28	0.66	0.19
62 and 62A	0.43	0.75	0.32
61 and 61A	0.06	0.64	0.04
			$\Sigma P(A_8, A_7) = 0.72$

The sum of the items in the last column in Table XI is the estimate that any natural condition between the 700- and 850-mb levels will be approximated by the Standard Atmospheres defined in this report.

One further remark may be made concerning the 28 percent (approximately) of cases which would resemble one Atmosphere at 700 mb, and another at 850 mb. The distributions of Fig. 5 are consistently skewed towards lower temperatures. An obvious cause of this

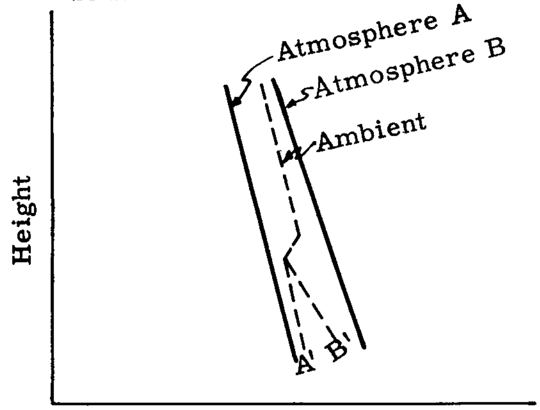


Fig 6 -- Schematic temperature inversion in the vertical

could be the prevalence of temperature inversions in the lower levels. A schematic representation of such inversions is shown in Fig. 6.

The temperature inversion shown might be due to frontal over-running, ie, a frontal zone at several thousand feet above the ground, with warm air (typical of Atmosphere B) above cooler air (typical of Atmosphere A). The ambient structure might extend, below the inversion, to either A' or B'. The latter case might apply if the ground under the cooler air mass is considerably warmer than the air mass, as a result of previous thermal exposures. This condition seems to be quite prevalent in Europe, for example, according to data in Reference 9. Therefore, it may be inferred that in some cases, when 700-mb and 850-mb temperatures are not typical of a single theoretical atmosphere, levels lower than 850 mb do have temperatures representative of the atmosphere defining the 700-mb temperature.

It is concluded that the Standard Atmospheres herein defined will approximate natural conditions over the Northern Hemisphere at least 70 percent of the time.

APPENDIX A

1.

$$\Delta z = \frac{R\overline{T}}{g} \ln \frac{P_1}{P_2},$$

where Δz = thickness in centimeters of layer included between lower-level pressure P_1 and higher-level pressure P_2,

R = gas constant for air $\left(2.87 \times 10^6 \frac{\text{ergs}}{\text{gm deg}}\right)$,

g = acceleration of gravity $\left(980 \frac{\text{cm}}{\text{sec}^2}\right)$, and

$\overline{T}$ = mean virtual temperature of layer (in degrees Kelvin).

Then

$$\Delta z = \frac{\left(2.87 \times 10^6 \frac{\frac{\text{gm cm}^2}{\text{sec}^2}}{\text{gm deg}}\right)(\overline{T}\text{ deg})}{980 \frac{\text{cm}}{\text{sec}^2}} \ln \frac{P_1}{P_2}$$

$$= \left[2928.6\ \overline{T} \ln \frac{P_1}{P_2}\right] \text{cm} \times \frac{1 \text{ ft}}{30.48 \text{ cm}}$$

$$\Delta z = \left(96.08\ \overline{T} \ln \frac{P_1}{P_2}\right) \text{ft}$$

2. In the layer from 700 mb to 300 mb:

$$\Delta z = 96.08\ \overline{T} \ln \frac{700}{300}$$

$$= 96.08\ \overline{T}\ (0.8473)$$

$$\Delta z = (81.41\ \overline{T}) \text{ ft}$$

3. $D\left(\frac{\text{lbs}}{\text{ft}^3}\right) = \frac{0.021746\ P}{T}$ (P in mb, T in degrees Kelvin)

APPENDIX B

Temperature, pressure, and density at 2000-foot intervals are listed below. More detailed listings, for 100-foot intervals, are filed by Sandia Corporation, Division 5133. Symbols used in the listing below are defined as follows:

H = height above sea level in thousands of feet

T = temperature in degrees centigrade

P = pressure in millibars

D = density in pounds per cubic ft

Standard Atmospheres

H	Atmosphere 66A			Atmosphere 66		
	T	P	D	T	P	D
0	-41.07	1034.78	0.09695	-24.24	1034.39	0.09036
2	-38.29	946.75	0.08765	-25.44	952.52	0.08361
4	-36.38	866.76	0.07960	-27.06	875.42	0.07735
6	-36.05	793.85	0.07280	-29.11	803.59	0.07160
8	-36.05	727.00	0.06667	-31.58	737.02	0.06634
10	-36.05	666.59	0.06113	-34.47	676.08	0.06159
12	-38.85	610.32	0.05664	-37.99	619.59	0.05729
14	-42.57	558.00	0.05262	-41.76	566.56	0.05324
16	-46.26	509.31	0.04881	-45.48	517.45	0.04942
18	-49.92	464.04	0.04520	-49.16	471.91	0.04581
20	-53.55	422.26	0.04181	-52.77	430.04	0.04243
22	-57.15	383.75	0.03863	-56.39	391.29	0.03925
24	-60.72	348.39	0.03566	-60.03	354.61	0.03618
26	-61.26	315.83	0.03241	-60.95	321.57	0.03295
28	-61.26	286.40	0.02939	-60.95	291.31	0.02985
30	-61.26	259.51	0.02663	-60.95	263.99	0.02705
32	-61.26	235.05	0.02412	-60.95	239.29	0.02452
34	-61.26	213.22	0.02188	-60.95	217.24	0.02226
36	-61.26	193.44	0.01975	-60.95	196.94	0.02018
38	-61.26	175.31	0.01799	-60.95	178.49	0.01829
40	-61.26	158.74	0.01629	-60.95	161.71	0.01657
42	-61.26	143.83	0.01476	-60.95	146.87	0.01505
44	-61.26	130.77	0.01342	-60.95	133.21	0.01365
46	-61.26	118.69	0.01218	-60.95	120.62	0.01236
48	-61.26	107.58	0.01104	-60.95	109.20	0.01119
50	-61.26	97.35	0.00999	-60.95	98.76	0.01012
52	-61.26	88.09	0.00904	-60.95	89.39	0.00916
54	-61.26	79.71	0.00818	-60.95	81.10	0.00831
55	-61.26	75.81	0.00778	-60.95	77.39	0.00793

Standard Atmospheres

H	Atmosphere 65A			Atmosphere 65		
	T	P	D	T	P	D
0	-23.29	1019.49	0.08872	-10.50	1019.00	0.08436
2	-21.06	939.32	0.08102	-12.47	942.43	0.07861
4	-20.06	864.46	0.07428	-14.84	869.93	0.07323
6	-20.31	796.40	0.06849	-17.62	801.83	0.06823
8	-21.80	733.56	0.06346	-20.78	738.16	0.06360
10	-24.52	674.97	0.05903	-24.33	679.15	0.05935
12	-28.45	619.85	0.05508	-28.26	624.62	0.05546
14	-32.47	569.16	0.05142	-32.15	573.59	0.05175
16	-36.25	521.76	0.04789	-35.91	525.88	0.04820
18	-40.20	477.38	0.04456	-39.85	481.21	0.04485
20	-44.20	436.24	0.04143	-43.84	439.66	0.04169
22	-47.97	398.18	0.03845	-47.58	401.37	0.03869
24	-51.71	362.65	0.03561	-51.38	365.63	0.03585
26	-55.40	329.37	0.03289	-55.25	332.21	0.03315
28	-56.32	299.36	0.03002	-56.02	301.87	0.03023
30	-56.32	272.43	0.02732	-56.02	274.70	0.02751
32	-56.32	247.60	0.02483	-56.02	249.74	0.02501
34	-56.32	224.67	0.02253	-56.02	226.87	0.02272
36	-56.32	203.93	0.02045	-56.02	205.90	0.02062
38	-56.32	185.18	0.01857	-56.02	187.03	0.01873
40	-56.32	168.42	0.01689	-56.02	170.25	0.01705
42	-56.32	153.17	0.01536	-56.02	154.58	0.01548
44	-56.32	139.21	0.01396	-56.02	140.59	0.01408
46	-56.32	126.34	0.01267	-56.02	127.71	0.01279
48	-56.32	114.67	0.01150	-56.02	115.93	0.01161
50	-56.32	140.00	0.01043	-56.02	105.15	0.01053
52	-56.32	94.53	0.00948	-56.02	95.36	0.00955
54	-56.32	86.15	0.00846	-56.02	86.67	0.00868
55	-56.32	82.46	0.00827	-56.02	82.88	0.00830

Standard Atmospheres

H	Atmosphere 64A			Atmosphere 64		
	T	P	D	T	P	D
0	-7.93	1019.93	0.08362	6.97	1019.94	0.07917
2	-7.31	942.99	0.07713	2.67	946.32	0.07460
4	-6.93	871.96	0.07122	-1.52	877.09	0.07021
6	-6.93	806.34	0.06586	-5.61	811.83	0.06598
8	-9.66	745.36	0.06151	-9.60	750.74	0.06194
10	-13.84	688.95	0.05777	-13.55	693.41	0.05808
12	-17.98	635.81	0.05418	-17.85	639.43	0.05446
14	-22.09	585.85	0.05074	-21.97	588.91	0.05098
16	-26.17	538.86	0.04744	-25.92	541.78	0.04765
18	-30.21	494.85	0.04429	-29.72	497.62	0.04445
20	-34.22	453.61	0.04128	-33.79	456.51	0.04147
22	-38.19	415.15	0.03842	-37.80	418.13	0.03863
24	-42.14	379.29	0.03570	-41.75	382.37	0.03593
26	-46.04	346.03	0.03313	-45.65	349.25	0.03338
28	-49.92	315.28	0.03071	-49.50	318.75	0.03099
30	-53.76	286.85	0.02843	-53.31	290.28	0.02871
32	-57.57	260.65	0.02629	-57.05	263.56	0.02652
34	-61.35	236.80	0.02431	-60.74	238.75	0.02444
36	-61.53	214.98	0.02209	-61.11	216.78	0.02223
38	-61.53	195.42	0.02008	-61.11	196.60	0.02016
40	-61.53	177.22	0.01821	-61.11	178.26	0.01828
42	-61.53	160.48	0.01649	-61.11	161.39	0.01655
44	-61.53	145.11	0.01491	-61.11	146.37	0.01501
46	-61.53	131.19	0.01348	-61.11	132.72	0.01361
48	-61.53	118.54	0.01218	-61.11	120.33	0.01234
50	-61.53	107.34	0.01103	-61.11	109.02	0.01118
52	-61.53	97.61	0.01003	-61.11	98.78	0.01013
54	-61.53	89.14	0.00916	-61.11	89.62	0.00919
55	-61.53	85.45	0.00878	-61.11	85.42	0.00876

Standard Atmospheres

H	Atmosphere 63A			Atmosphere 63		
	T	P	D	T	P	D
0	10.37	1010.01	0.07746	17.65	1009.88	0.07551
2	7.15	938.10	0.07277	13.39	939.59	0.07130
4	3.99	870.54	0.06830	9.17	873.31	0.06726
6	0.87	807.19	0.06405	5.01	810.80	0.06338
8	-2.18	747.69	0.06000	0.89	751.91	0.05966
10	-5.20	692.30	0.05618	-3.17	696.43	0.05609
12	-8.17	640.64	0.05257	-7.19	644.47	0.05269
14	-11.61	591.78	0.04920	-11.23	595.64	0.04945
16	-15.80	545.96	0.04613	-15.42	549.74	0.04638
18	-19.96	503.13	0.04321	-19.58	506.82	0.04346
20	-24.10	463.19	0.04044	-23.71	466.56	0.04067
22	-28.16	425.77	0.03779	-27.79	429.03	0.03802
24	-32.18	390.87	0.03527	-31.82	393.78	0.03548
26	-36.18	358.23	0.03287	-35.83	360.93	0.03307
28	-40.16	327.78	0.03059	-39.82	330.40	0.03079
30	-44.13	299.55	0.02844	-43.78	301.90	0.02862
32	-47.91	273.37	0.02639	-47.55	275.67	0.02657
34	-51.72	249.09	0.02446	-51.35	251.34	0.02464
36	-55.54	226.58	0.02264	-55.18	228.66	0.02281
38	-59.37	205.68	0.02092	-59.05	207.57	0.02108
40	-63.21	186.34	0.01930	-62.94	188.03	0.01945
42	-67.06	168.62	0.01779	-66.86	170.01	0.01792
44	-70.91	152.44	0.01639	-70.82	153.35	0.01648
46	-71.09	137.25	0.01477	-71.01	138.33	0.01488
48	-71.09	124.05	0.01335	-71.01	124.76	0.01342
50	-71.09	111.97	0.01205	-71.01	112.49	0.01210
52	-71.09	100.92	0.01086	-71.01	101.42	0.01091
54	-71.09	90.88	0.00978	-71.01	91.57	0.00985
55	-71.09	86.33	0.00929	-71.01	86.92	0.00935

Standard Atmospheres

H	Atmosphere 62A			Atmosphere 62		
	T	P	D	T	P	D
0	19.04	1004.75	0.07477	27.27	1005.00	0.07247
2	15.84	935.55	0.07039	23.17	937.34	0.06878
4	12.60	870.14	0.06621	19.12	873.32	0.06497
6	9.32	808.70	0.06225	15.12	812.96	0.06132
8	6.00	750.80	0.05848	11.16	755.89	0.05781
10	2.64	696.73	0.05493	7.24	702.27	0.05446
12	-0.66	645.75	0.05153	3.06	651.54	0.05129
14	-3.90	597.96	0.04829	-1.09	603.96	0.04827
16	-7.05	553.14	0.04520	-5.20	558.97	0.04536
18	-10.13	511.42	0.04228	-9.26	516.99	0.04260
20	-14.00	472.32	0.03963	-13.41	477.57	0.03998
22	-18.19	435.48	0.03714	-17.61	440.58	0.03749
24	-22.35	401.04	0.03477	-21.78	405.77	0.03510
26	-26.48	368.80	0.03251	-25.91	373.29	0.03283
28	-30.52	338.78	0.03036	-29.97	342.89	0.03066
30	-34.45	310.78	0.02831	-33.91	314.57	0.02859
32	-38.38	284.61	0.02636	-37.84	288.18	0.02663
34	-42.32	260.19	0.02451	-41.78	263.46	0.02476
36	-46.26	237.49	0.02285	-45.72	240.67	0.02301
38	-50.21	216.55	0.02112	-49.66	219.33	0.02134
40	-54.12	197.03	0.01956	-53.60	199.62	0.01977
42	-57.83	179.14	0.01809	-57.32	181.54	0.01829
44	-61.52	162.54	0.01670	-61.02	164.77	0.01689
46	-65.18	147.10	0.01538	-64.69	149.17	0.01556
48	-68.82	132.97	0.01415	-68.33	134.89	0.01432
50	-72.43	119.82	0.01298	-71.95	121.96	0.01318
52	-72.43	108.09	0.01171	-71.95	109.65	0.01185
54	-72.43	97.38	0.01055	-71.95	99.29	0.01073
55	-72.43	92.49	0.01002	-71.95	94.75	0.01024

Standard Atmospheres

H	Atmosphere 61A			Atmosphere 61		
	T	P	D	T	P	D
0	30.09	999.95	0.07170	40.23	999.79	0.06937
2	27.04	933.28	0.06760	35.83	935.30	0.06582
4	24.06	870.57	0.06369	31.41	874.02	0.06240
6	21.16	811.31	0.05994	26.97	815.73	0.05910
8	18.33	755.65	0.05637	22.51	760.64	0.05594
10	15.57	703.35	0.05297	18.03	708.56	0.05291
12	12.88	654.58	0.04976	13.55	659.40	0.05001
14	8.77	608.22	0.04691	9.23	612.98	0.04720
16	4.46	564.45	0.04421	4.92	568.97	0.04449
18	0.11	523.31	0.04164	0.57	527.72	0.04192
20	-4.27	484.74	0.03920	-3.80	488.67	0.03945
22	-8.60	448.21	0.03684	-8.15	452.14	0.03710
24	-12.86	414.06	0.03459	-12.42	417.64	0.03483
26	-17.04	381.98	0.03243	-16.60	385.34	0.03266
28	-21.13	352.11	0.03038	-20.70	355.15	0.03059
30	-25.30	323.95	0.02842	-24.85	326.82	0.02862
32	-29.43	297.59	0.02655	-28.98	300.38	0.02675
34	-33.52	273.08	0.02478	-33.08	275.58	0.02496
36	-37.58	250.04	0.02308	-37.14	252.46	0.02326
38	-41.60	228.74	0.02148	-41.17	230.98	0.02165
40	-45.59	208.89	0.01996	-45.16	211.06	0.02013
42	-49.52	190.47	0.01852	-49.11	192.37	0.01867
44	-53.42	173.41	0.01716	-53.01	175.15	0.01730
46	-57.32	157.63	0.01588	-56.90	159.32	0.01602
48	-61.21	142.99	0.01467	-60.80	144.44	0.01479
50	-65.10	129.46	0.01353	-64.69	130.77	0.01364
52	-68.98	117.00	0.01246	-68.57	118.27	0.01257
54	-72.85	105.66	0.01147	-72.44	106.79	0.01157
55	-74.79	100.35	0.01100	-74.38	101.47	0.01110

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